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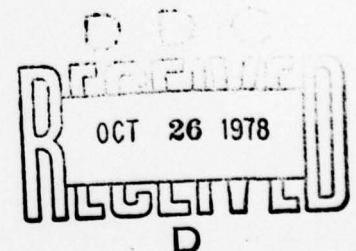
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DYNAMICS OF VORTICES AND SHOCK WAVES
IN NONUNIFORM MEDIA

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INTRODUCTION

A research program studying the dynamics of high-energy vortex rings produced by gasdynamic-pulse techniques has been initiated. Shock-wave acceleration of air at the mouth of an open tube permits generation of very strong vortex rings (Reynolds number based on circulation, $Re = \Gamma/\nu$, of order 400,000) with highly concentrated vorticity (core radius/ring radius ≈ 0.1). In fact, during the present research project vortex rings have been generated which are so strong that maximum velocities in the core of the vortex are near sonic velocity.

Instrumentation systems and measurement techniques have been developed for studying shock-produced vortex rings, and preliminary measurements have been made. The project is designed to focus on the mechanisms of turbulence production and damping in vortex rings and on the mechanisms of vortex-ring instability. These processes are currently of great interest in the effort to understand how large-scale, coherent motions which occur in vortex rings and shear layers contribute to dissipation and mixing at small scales. The work is directed at studying the properties of high-energy vortex rings prior to the occurrence of instability, and also certain characteristics of the instability as it occurs in very strong vortex rings.

DESCRIPTION OF WORK

During the past year the major effort has been to further the development of the apparatus described in the Final Scientific Report of Contract F44620-76-0082, dated 1 July 1977, and to develop a laser-spark velocimeter.

A more extensive effort than was originally anticipated was required to construct a high-quality spark-schlieren optical system from existing components available in the GALCIT laboratories. However, the system is now complete and tests show that it meets design criteria. The entire system slides along rails which are aligned parallel to the axis of the shock-tube vortex generator, so that different stages of vortex-ring development can be studied as the ring propagates away from the mouth of the vortex generator.

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A non-intrusive method for measuring fluid velocity and deformation by heating a small volume of fluid with a laser spark and then detecting motion of the tagged fluid with a schlieren optical system has been developed. Feasibility was first demonstrated by spark heating the fluid with an electrical discharge between two electrodes and subsequently measuring the velocity and circulation in a vortex ring using an earlier version of the schlieren system. Then a Hughes Model 302 pulsed ruby laser available in the GALCIT laboratories was modified for Q-switched operation so that most of the available optical energy is dumped into the fluid in a single pulse. The laser beam is focused to cause an estimated 0.5 j of energy in the pulse to be deposited into a volume of approximately 10^{-6} cm^3 . This energy density is sufficient to vaporize small amounts of solid (absorbing) material present in the focal volume. Thus, the technique consists of seeding the fluid passing through the focal volume with, say, graphite powder to provide nuclei for initiation of the laser spark. This artifice is required of a system operating in the visible spectrum. On the other hand, infrared radiation, such as that emitted by a CO_2 laser, is absorbed sufficiently by naturally-occurring impurities in room air that seeding is not necessary.

Figure 1 is a spark-schlieren photograph of the disturbance generated by the vaporization of two specks of graphite in still air 70 μsec after firing the ruby laser. It is clear from the photograph that the schlieren system yields sufficient sensitivity that local values of both fluid velocity and sound speed can be determined at certain points in the flow; the former by measuring displacement of the heated volume of fluid in time sequences of photographs or by real-time optical detections, and the latter by subtracting the observed velocity of the acoustic disturbance generated by the laser spark from the previously determined fluid velocity. The method suffers from the disadvantage that motion over a finite, measurable distance must be observed in order to deduce velocity, so the velocity is not a point measurement. Furthermore, if the schlieren data are recorded on photographs, then the data-acquisition is a tedious process. (On the other hand, real-time data readout from a reticon array detector, applying pattern-recognition techniques to the digitized data, is a technique which readily lends itself to this application.) In any case, there is no other nonintrusive

method for measuring true fluid velocity in high-energy vortex rings in un-seeded air, so the method is potentially very important. Furthermore, the method provides the opportunity of measuring (albeit with somewhat more complicated procedures for data gathering) the deformation of the marked volume of fluid. Therefore, the rate of strain in the vortex ring, a quantity of primary interest in the study of the dynamics of vortex rings, can also be measured.

Preliminary experiments utilizing the laser-spark anemometer have been carried out. Figure 2 shows two pictures of high-energy vortex rings ($Re \sim 5 \times 10^5$, diameter = 5 cm) about two diameters away from their origin. The spark-schlieren photographs are side views of the rings, in which the dilated core region appears as the dark elongated dumbbell shape, with a bright line along the center. Graphite particles, originally placed on the edge of the nozzle that generates the vortices, are seen as a dark stream being convected into and distributed around the core. The first picture shows a line formed in the fluid, about 5 microseconds after many of the particles are vaporized by firing a concentrated (Q-switched and focused) ruby laser pulse. The tiny explosions produce spherical waves forming a cylindrical envelope, which can also be seen. The second picture shows the line after 250 microseconds, when it has been stretched and wrapped around the core by convecting with the local flow. It is possible to deduce from the shape of the line, the local velocities and the deformation of the fluid surrounding the core. Due to the tremendous flow accelerations (initially by pressure waves and later by vortex centrifugal forces), the high density graphite particles -- even the finest ($< 1 \mu$) -- cannot keep up with the fluid in the center of the core. Thus, measurements are possible at a radius only as small as the radius of closest approach by the particles to the core center, which is approximately 1.15 cm for the shown vortex ring. At this radius, the maximum observed local velocity and rate of deformation are estimated at 57 m/s and 1.15 s^{-1} , respectively. The difficulty with distributing particles for obtaining measurements in the core can be eliminated if infrared laser absorption by trace vapors of organic molecules (e.g., Benzene) is used to generate a spark (cf. below).

The fact that the line of laser-heated fluid remains smooth, even after being subjected to such strong deformation until it wraps itself around the core, is valuable proof of the quiescence or absence of turbulent fluctuations in this region around the core. The preliminary shadow photographs of such vortex rings presented in the progress report of 1 July 1977, showed features which were not understood at the time and needed further investigation. Beside the dark shadow representing the viscous core center, there occurred hollow cylindrical shadows within which extensive mixing seemed to have taken place to make the flow there relatively uniform. Outside the hollow shadow, the flow showed elongated striations showing the presence of strong gradients. It was not clear if this residue of the separated turbulent boundary layers containing small eddies, which is ingested by the vortex during the late stage of its formation and is subsequently torn apart and processed by the strong deformation field around the vortex core, still remained turbulent. Such disturbances, originating outside the vortex, play the same role in the dynamics of vortices as does the "turbulence" observed in other so-called turbulent vortices (e.g., aircraft trailing vortices), and are also the prime candidates for providing the necessary perturbations to excite the inherent (Widnall) instability of vortex rings. Figure 2 demonstrates the absence of fluctuations in this region outside the hollow cylindrical shadow, and supports the thesis that the deformation process about the vortex core actually tends to suppress such fluctuations.

In principle, the important term in the turbulent energy equation is (Tennekes & Lumley, 1974)

$$\frac{D}{Dt} \left(\frac{\overline{u'^2}}{2} \right) \approx \frac{\Gamma}{\pi r^2} \overline{u'_r u'_\theta} \quad , \quad (1)$$

where ()' refers to fluctuating quantities, $-\Gamma/2\pi r^2$ is the rate of strain in the vortex flow field (r is the distance from the vortex center), and u'_r and u'_θ are the components of radial and azimuthal velocity fluctuations, respectively. The term on the r.h.s. of (1) is the production of turbulence by mean strain, and is usually described in terms of a vortex-stretching mechanism. Consider a boundary layer shedding from the bottom wall of

a vortex generator and rolling up to form a vortex with clockwise circulation as indicated in figure 3. In this case the Reynolds stress in the boundary layer, $\overline{u'_x u'_y}$, is negative. It is reasonable to assume that as the shed boundary layer is ingested into the vortex ring, what was $\overline{u'_x u'_y}$ in the boundary layer simply becomes $\overline{u'_r u'_\theta}$ in the vortex (cf. figure 3), so that also $\overline{u'_r u'_\theta} < 0$. If this is the case, then the turbulent energy equation indicates that, in the strain field of the vortex, fluctuations are damped. This is in excellent agreement with our preliminary experimental observations. In summary, since in the process of conversion from the boundary layer to the vortex the strain field changes sign, as shown in figure 3, the mechanism of vortex stretching changes from a turbulence-producing effect in the boundary layer to a damping effect in the vortex. Knight and Saffman (1978) have calculated the decay of turbulence in a line vortex due to the straining mechanism, and it is hoped that further experiments will provide data that can be compared with the results of those calculations.

The major source of error in tracking a heated spot of fluid for the purpose of measuring velocity and fluid deformation is possible motion of the lighter hot fluid relative to the mean (local) fluid motion in an accelerating flow field. This problem has been carefully analyzed by Rudinger and Somers (1959) and criteria can be established for the operating conditions necessary to insure suitable accuracy.

Unfortunately, the necessity of "seeding" the air with solid particles when a laser emitting visible radiation is used to heat the spot of fluid introduces undesirable uncertainty in the size and density of the spark-heated region (cf. figure 1), because of inevitable nonuniformities in the density of seeded material, and also unnecessarily intrudes upon the flow prior to firing the laser. It is known that seeding is not necessary if the pulsed laser emits in the infrared because of the increased absorption of infrared radiation by practically all substances, especially solids and water vapor. Thus, even trace vapors of organic substances can be used to induce uniform and controlled heating, and it is intended to develop the technique in this direction.

Because it has recently become clear that the central result obtained in studies undertaken earlier under this grant of the propagation of shock waves through a random medium is much more closely related to our

present interests than had previously been suspected, we briefly review the results here. The rather spectacular change across the shock wave of the character of the random medium in the experiment pictured in the schlieren photograph (figure 4; shock propagating from left to right) is thought to be due to the generation of concentrated vorticity by interaction of the shock wave with density inhomogeneities. Particularly important is the tendency of the white streaks appearing behind the shock wave to be oriented parallel to the plane of the shock wave. In effect, the rather isotropic distribution of density fluctuations pictured ahead of the shock wave has been converted into a rather more ordered structure by the action of the shock wave. The generation of vorticity by vortex stretching and because of entropy gradients is shown by the vorticity equation

$$\frac{\partial \underline{w}}{\partial t} = \nabla \times (\underline{u} \times \underline{w}) + \nabla T \times \nabla s ,$$

which can also be written in the form

$$\frac{D(\underline{w}/\rho)}{Dt} = \frac{(\underline{w} \cdot \nabla) \underline{u}}{\rho} - \frac{\nabla p \times \nabla \rho}{\rho^3} . \quad (2)$$

The second term on the right-hand-side of (2) is known as the Bjerknes vorticity term; it shows that the pressure gradient in the shock wave interacts with the component of the density gradient parallel to the plane of the shock to produce vorticity in the plane of the shock. Indeed, interaction of a shock with a spherical volume containing fluid of different density than the surroundings produces a vortex ring, as was observed, e.g., in the experiments of Markstein (1958). Whether or not the characteristics observed in figure 4 can be explained in terms of vorticity aligned parallel to the shock wave, i.e., some random configuration of vortex-ring like structures, deserves further consideration and analysis.

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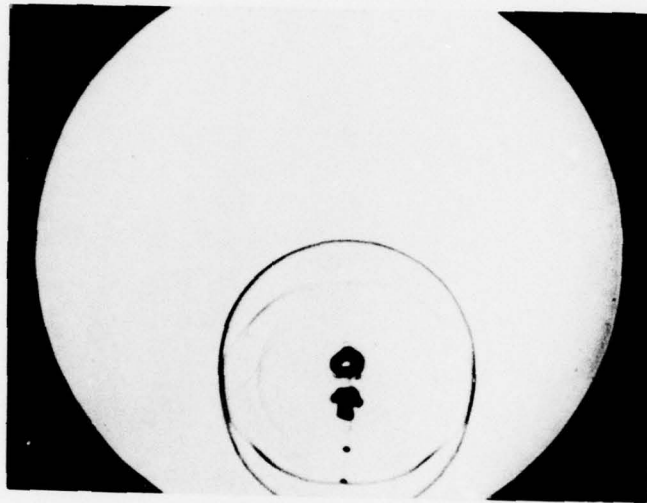
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PROFESSIONAL PERSONNEL

Bradford Sturtevant, Professor of Aeronautics
 Vijay A. Kulkarny, Research Fellow in Aeronautics



**Figure 1 Two Hot Spots Generated By Laser
Spark In Seeded Air**

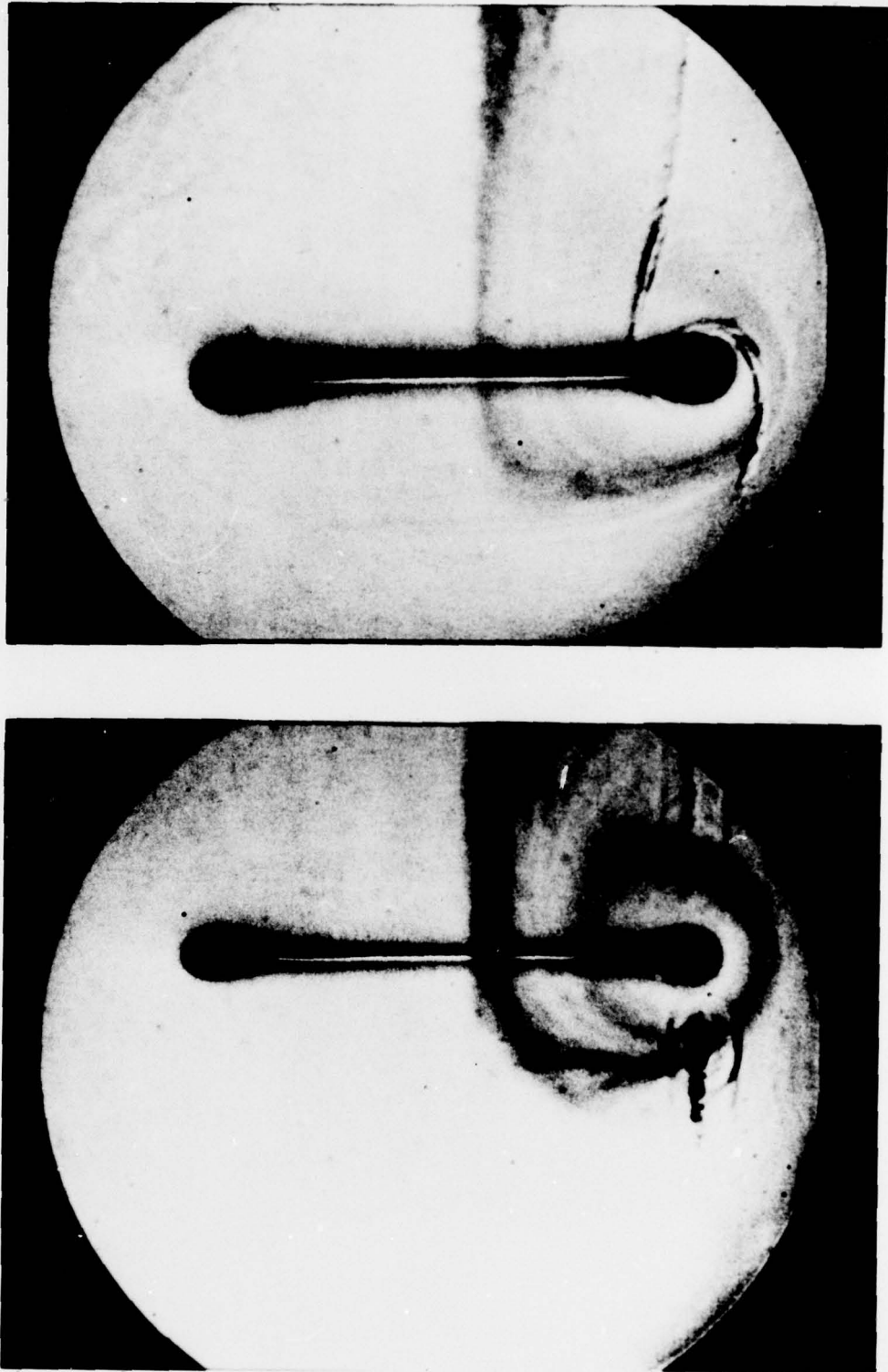


Figure 2 Deformation Of Laser Spark Line Around Vortex Ring Core

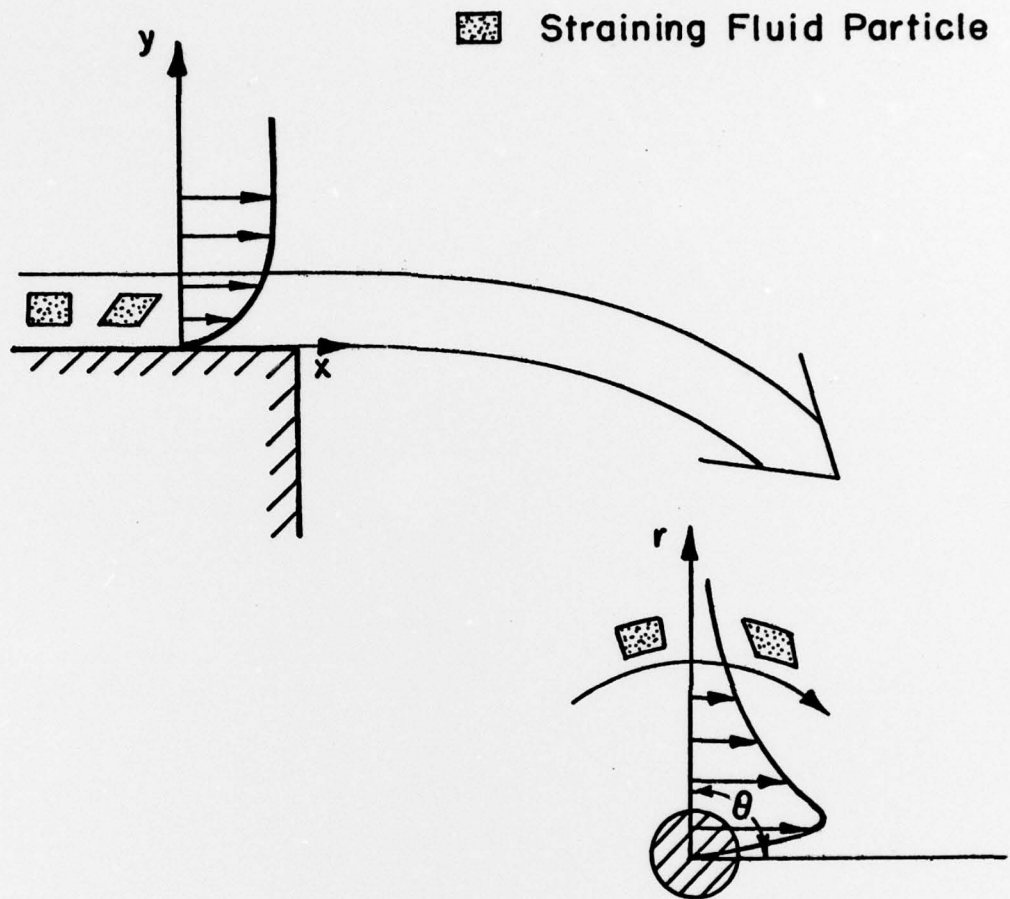


Figure 3. Schematic Of Shear Layer Rolling Up Into Vortex Showing Strain Field

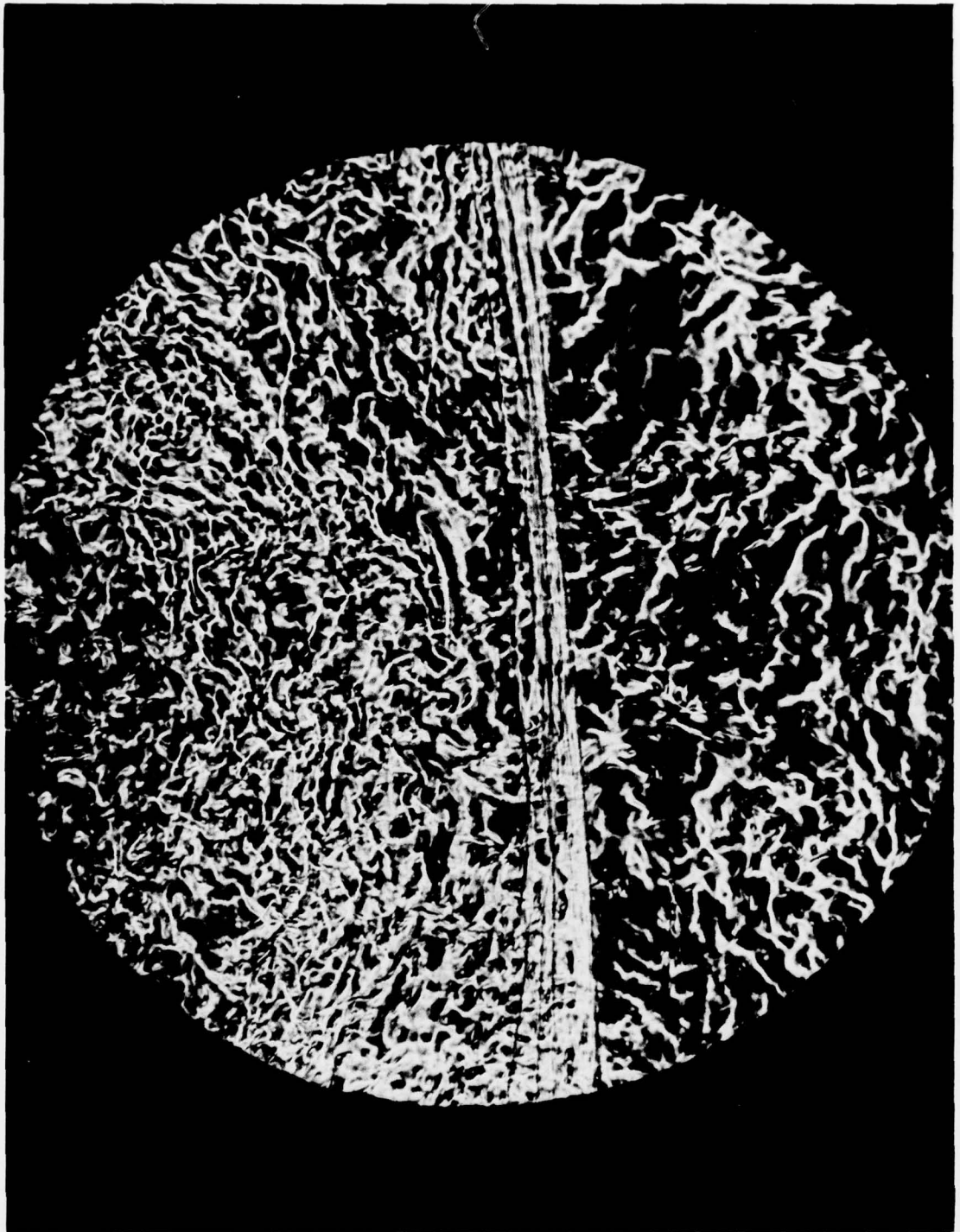


Figure 4 Shock wave propagating
through random medium